VERSATILE THIN-FILM PHOTOVOLTAIC LASER SCRIBING SYSTEM

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ABSTRACT: We present a laser scribing system for mid-size photovoltaic modules (up to 410 × 520 mm^2) implementing a movable diode-pumped solid state laser. In this configuration, the heavy large-area photovoltaic module does not need to be displaced, allowing for faster and overall more compact industrial systems. Furthermore, in the vicinity of the thin-film, critical beam parameters such as the depth of focus are kept constant throughout the scribing process.
Keywords: Laser Processing, Module Manufacturing, Thin Film

1 INTRODUCTION

Unlike traditional wafer-based silicon solar cells, the individual cells of a thin-film photovoltaic (PV) module can be serially interconnected without the need of expensive and time-consuming wiring. Instead of wiring, 3 patterns (p1, p2, p3) are micromachined by laser scribing during fabrication [1]. The development of a fast, accurate, and reliable laser scribing system is one of the key issues in reducing the cost of thin-film PV modules.

Industrial laser scribing requires ultra-stable high-repetition rate (10–150 kHz) microjoule short pulses of a few nanoseconds or less. Laser devices have thus been essentially limited to well-established Q-switched diode-pumped solid-state lasers (DPSSL). The active medium of such lasers is either a fundamental, frequency-doubled, or frequency-tripled neodymium-doped crystal emitting at 1064 nm, 532 nm and 355 nm, respectively. New opportunities have arisen with the recent advent of *movable* DPSSL.

Current in-line systems have a limited throughput and are extremely large with respect to the module size, because they rely on a beam delivery scheme that requires the heavy large-area PV module to be displaced. The purpose of this work is to investigate an advanced beam delivery scheme based upon a movable DPSSL.

2 LASER SCRIBING SYSTEM SETUP

2.1 Mechanical setup

As pictured in Fig. 1, we built a versatile laser scribing system consisting of a substrate holder, a movable optical table, a fixed optical table, a suction system, and cable carriers. The substrate holder is mounted horizontally on a translation stage, while the movable optical table is mounted vertically on a gantry. The substrate holder can accommodate various small and mid-size PV modules up to 410 × 520 mm^2. The suction system holds the substrate in place during motion and collects material removal during the scribing process. Both the movable optical table and the substrate holder may be precisely displaced in the x- and y- direction up to 3 m/s. Two cable carriers assure the unobstructed motion of all cables when the movable optical table is displaced. The fixed optical table is attached sideways to the system. The displacement axes of the substrate holder (x_s, y_s) and the displacement axes of the movable optical table (x_o, y_o) are illustrated in Fig. 1. Axes specifications are reported in Table I.

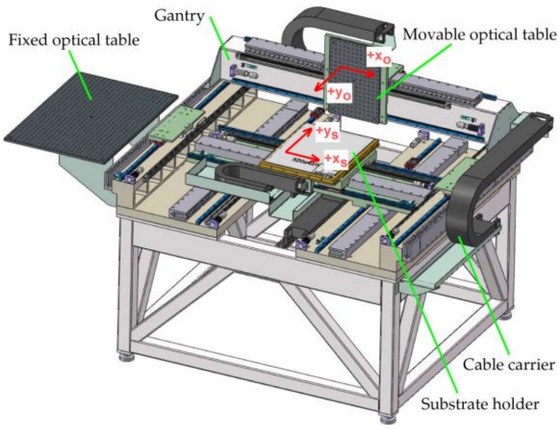

Figure 1: Versatile thin-film photovoltaic laser scribing system.

Table I: System specifications

Moving part	sub. holder		opt. table	
Direction	x_s	y_s	x_o	y_o
Stroke [mm]	902	1032	1172	1052
Max. speed [m/s]	3	3	3	3
Max. acceleration [g]	3	3	3	3
Position accuracy [µm]	<10	<10	<10	<10
Repeatability [µm]	5	5	5	5

2.2 Optical setup

As illustrated in Fig. 2, the versatile thin-film PV laser scribing system has been configured in the following ways:

- **Traditional beam delivery schemes.** A high-power DPSSL is mounted on the fixed optical table. The output beam is expanded and guided towards a mirror that is mounted on the movable optical table. This mirror guides the beam towards a lens that focuses the beam onto the PV module. During the scribing process, either the substrate is moved and the mirror is fixed, or the substrate is fixed and the mirror is moved.

- **Movable DPSSL-based beam delivery scheme.** A robust and compact DPSSL—which can withstand accelerations of up to several g while in operation—is mounted on the movable optical table. The laser beam is expanded and focused again onto the PV module, which does not need to be displaced during the scribing process.

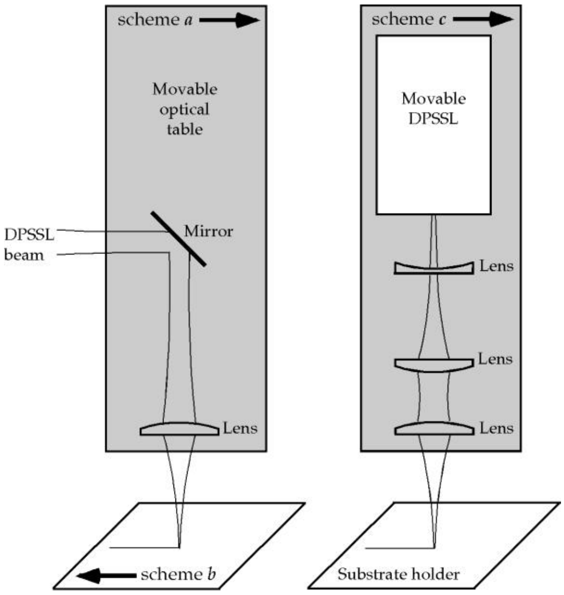

Figure 2: Optical configurations of the versatile thin-film photovoltaic laser scribing system. In traditional beam delivery schemes, either the optical table (scheme *a*) or the substrate holder (scheme *b*) is moved during the scribing process. In the movable DPSSL-based beam delivery scheme (scheme *c*), the whole optical setup is displaced during the scribing process.

2 RESULTS AND DISCUSSION

Scribed lines must be narrow and closely aligned with each other in order to minimize the dead area comprised between the first and the third pattern. We investigated the straightness of lines that were scribed over the full length of mid-size PV modules (410 × 520 mm^2). The system axes were driven at 2 m/s under the various optical schemes presented in Fig. 2. No active compensation has been deployed in any of the schemes. In scheme *a*, angular errors of the movable optical table translate into relatively inaccurate lines, as pictured in Fig. 3. This scheme would require an optical or mechanical compensation mechanism to improve the straightness of scribed lines. In scheme *b* and *c*, the straightness is better than 10 μm (Fig. 3). Laser scribing systems relying on scheme *b*, however, have a footprint size that is at least twice the size of the substrate. This approach is particularly disadvantageous in the manufacture of large-area thin-film PV modules.

We also investigated the parallelism of lines that were scribed under scheme *c* over the full length of 410 × 520 mm^2 PV modules. At 2 m/s, the parallelism was better that 10 μm in the x_o and y_o directions. In industrial systems, the distance between lines is often kept constant with an on-the-fly line-tracking system. Given the parallelism of our scribed lines, such a system did not have to be implemented, at least when lines were scribed on mid-size PV modules up to 2 m/s with a movable DPSSL. This scheme has been successfully tested on various films. To illustrate, we present in Fig. 4 a close-up view of a P3 pattern micromachined on a micromorph tandem structure.

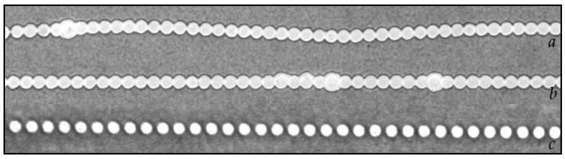

Figure 3: Straightness of lines investigated by optical microscopy. Three lines were scribed at 2 m/s under various optical configurations (the lines were manually juxtaposed in Fig. 3 for comparison purposes). The first and second lines from the top were scribed by displacing the mirror (*a*), and the substrate (*b*), respectively. The third line was scribed by displacing the whole optical setup including the movable DPSSL (*c*). The frequency repetition rate of our movable laser was not sufficient to process modules at 2 m/s.

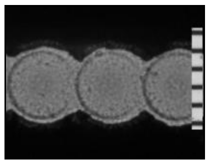

Figure 4: P3 pattern of a micromorph cell with a silver back reflector investigated by optical microscopy (graduation=10 μm). The line was scribed at 0.7 m/s using the DPSSL-based beam delivery scheme (scheme *c*).

In commercial large-area systems, the output of a high-power high-cost DPSSL is split into several beams in order to process several lines simultaneously. An approach based upon multiple small, low-cost, movable DPSSL removes the need of complex beam splitting and beam delivering optics. Furthermore, in the vicinity of the thin-film, critical beam parameters such as the depth of focus are kept constant for all lines throughout the scribing process.

CONCLUSIONS

A versatile laser scribing system for small and mid-size PV modules was built in order to test various laser architectures. It is found that compact and accurate industrial systems can be realized with a movable DPSSL.

[1] R. Bartlome, B. Strahm, Y. Sinquin, A. Feltrin, and C. Ballif, "Lasers in thin-film photovoltaics: a review", *in preparation.*